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Neutrinoless Double Beta Decay with SNO+

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Abstract. SNO+ will search for neutrinoless double beta decay by loading 780 tonnes of linear alkylbenzene liquid scintillator with O(tonne) of neodymium. Using natural Nd at 0.1% loading will provide 43.7 kg of ^{150}Nd given its 5.6% abundance and allow the experiment to reach a sensitivity to the effective neutrino mass of 100-200 meV at 90% C.L in a 3 year run. The SNO+ detector has ultra low backgrounds with 7000 tonnes of water shielding and self-shielding of the scintillator. Distillation and several other purification techniques will be used with the aim of achieving Borexino levels of backgrounds. The experiment is fully funded and data taking with light-water will commence in 2012 with scintillator data following in 2013.

1. Introduction

The use of the world's largest liquid scintillator detectors in the search for neutrinoless double beta decay is a promising development that has come to the fore in the last few years [1, 2]. These experiments push the trade-off between having a large mass of available isotope but lower energy resolution into a new regime. The re-use of the infrastructure from the SNO experiment [3] provides a cost-effective and ultra low-background detector to search for neutrinoless double beta decay. The first phase of the SNO+ experiment [1] will load about a tonne of natural neodymium (5.6% ^{150}Nd) into the scintillator. Future possibilities include neodymium enriched in ^{150}Nd or different isotopes that can be loaded at higher concentrations without significantly affecting the scintillator light output. While not covered here, a summary of the diverse range of other physics that will be probed by SNO+ including solar neutrinos, geo and reactor antineutrinos, supernovae can be found in [4].

2. Detector

The SNO+ detector is located 2 km underground (6000 m.w.e.) at Vale's Creighton nickel mine near Sudbury, Ontario, Canada. The expansion of the scientific facility with the creation of SNOLAB has produced the world's deepest operating scientific laboratory, of which the SNO+ experiment is part.

A barrel-shaped cavity 34 m high and 22 m wide filled with ultra pure water provides the space for the detector. A 17.8 m diameter geodesic stainless steel frame is suspended from the cavity deck and forms the PMT Support Structure (PSUP) that holds the approximately 9500 8-inch PMTs. Within the PSUP is a 12 m diameter 5.5 cm thick acrylic vessel (AV) with an internal volume of 907 m³. The primary change in the conversion of the SNO detector into SNO+ is the replacement of the heavy water in the AV with linear alkylbenzene (LAB) scintillator. The LAB with a density of about 0.86 g/cm³ will be buoyant in the water of the

cavity and so a rope-net system that passes over the top of the AV and anchors it to the floor is being installed.

The PMTs are offset from the scintillator in the AV by about 3 m and the intermediate water volume provides 1700 tonnes of shielding. Outside the PSUP there are a further 5700 tonnes of water that shield the detector from external backgrounds in the rock. The walls and floor of the cavity itself are lined with Urylon, which is expected to attenuate radon emanating from the walls by a factor of nearly 10^7 [3]. The Urylon liner on the floor of the cavity was successfully replaced in 2011 and now incorporates the anchors for the new AV hold-down system.

A new trigger and DAQ system has been developed for SNO+ due to the factor of about 45 more light expected from the scintillator compared to the Cherenkov light in the heavy water. A new radon-tight universal interface and cover gas system will be installed in 2012.

2.1. Scintillator Systems and Purification

The scintillator for SNO+ comprises of 780 tonnes of linear alkylbenzene (LAB) with 2g/L of 2,5-diphenyloxazole (PPO) as a wavelength shifter [5]. LAB was selected due to its compatibility with acrylic, high flash point, good light yield, low toxicity and good commercial availability. An extensive set of scintillator purification systems are under construction with the aim of reaching the purity levels (10^{-17} g/g of ^{238}U and ^{232}Th chain activities) achieved by the Borexino experiment [6]. The approach of Borexino is being followed for SNO+, in particular with regard to the cleanliness and vacuum leak tightness.

Multi-stage vacuum distillation of the LAB will be performed, prior to adding it to the detector. The low volatility of the heavy metal contaminants enable an extremely pure product to be produced. The distillation system will operate at 19 L/minute allowing the detector to be completely filled in 1-2 months. A concentrated PPO solution will be flash distilled under vacuum at a higher temperature; mixing with the bulk of the LAB will be done before it reaches the detector. A further purification step involves a steam-stripping process to remove the high volatility contaminants of the LAB which include the noble gases (e.g. Rn, Ar, Kr) and oxygen.

While the detector is operational it will be possible to recirculate the entire scintillator volume in 4 days (150 LPM) for in-situ repurification. A rotating-stage water extraction column that exploits the differences in solubility of contaminants in water vs. LAB will be used to remove elements such as Ra, K and Bi. Columns loaded with metal scavenger beads made by Johnson Matthey Plc (who acquired Reaxa LTD) will be used to remove Pb, Ra, Bi, Ac, and Th. The steam stripping process will also be used during recirculation, and the scintillator will be subject to micro-filtration.

2.2. Neodymium Loading and Purification

The Nd will be loaded into the LAB at the O(0.1%) level and NdCl_3 is the starting point. The technique that will be used to make a soluble Nd-compound is pH-controlled, solvent-solvent extraction [7]. The carboxylic acid used will be 3,5,5 trimethyl hexanoic acid (TMHA) and it will be pre-purified using a thin-film evaporator column. The NdCl_3 solution will be pre-purified using the pH-adjustment co-precipitation (self-scavenging) technique [8], which exploits the large difference in solubility between Nd and contaminants such as Th. Laboratory tests have demonstrated the effectiveness of this self-scavenging procedure. An important consideration for the Nd-loading procedure is whether the purification systems used during recirculation of the scintillator would remove the Nd and this has been demonstrated not to be an issue for the water extraction and stripping processes. The metal scavengers will not be used on the Nd-loaded scintillator, but will be used as a polishing stage to remove the last traces of Nd when required.

3. Neodymium

Neodymium is classed as a rare earth element but is actually widely distributed in the Earth's crust, being as common as nickel and copper. A common use for Nd is to make the high strength magnets found, for example, in hybrid cars, computer hard disks, wind turbines and the headphones for personal stereos. Natural Nd contains two radioisotopes, ^{150}Nd at 5.6% natural abundance and ^{144}Nd at 23.8%. The ^{144}Nd decays with a 1.91 MeV alpha and a half-life of 2.3×10^{15} years giving an activity of 7.5 kBq per tonne of natural Nd. The double beta decay of ^{150}Nd has been recently measured by the NEMO-3 collaboration using 36.55 g of isotope to have a half-life of $T_{1/2}^{2\nu} = 9.11^{+0.25}_{-0.22}(\text{stat}) \pm 0.63(\text{syst}) \times 10^{18}$ years [9]; the half-life for neutrinoless double beta decay is found to be $T_{1/2}^{0\nu} > 1.8 \times 10^{22}$ years in the same experiment and is currently the world's best limit.

4. Sensitivity to Neutrinoless Double Beta Decay

With 0.1% loading SNO+ will use 0.78 tonnes of neodymium and contain 43.7 kg of ^{150}Nd with no enrichment. Nd has the largest phase space factor of all double beta decay isotopes and an endpoint of 3.37 MeV that places it above most backgrounds from natural radioactivity.

Backgrounds include the $2\nu\beta\beta$ from ^{150}Nd , ^8B solar neutrinos, ^{208}Tl and ^{214}Bi . These backgrounds are shown in Figure 1 along with a $0\nu\beta\beta$ signal assuming an effective neutrino mass of 350 meV. Gaussian smearing was applied under the assumption that 400 photoelectrons are

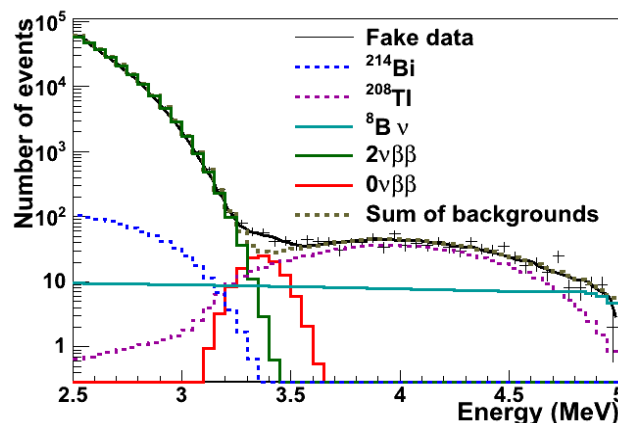


Figure 1. Simulated event energy spectrum showing the signal corresponding to an effective neutrino mass of 350 meV for a 3 year run with 0.1% Nd-loading.

detected per MeV. ^{214}Bi can be tagged, using the decay of its daughter isotope ^{214}Po in delayed coincidence, with high efficiency and a conservative 90% tagging efficiency is assumed for all sensitivity calculations. Figure 2 shows the evolution of the half-life and mass sensitivity over a 3 year run. The IBM-2 matrix element [10] that includes the effect of nuclear deformation is used to calculate the effective neutrino mass sensitivity. A fiducial volume of 50% of the AV, 80% detector livetime and backgrounds equivalent to those achieved in Borexino were used in the sensitivity calculations. There are avenues for improvement in all those areas and additionally, an optimisation of the trade off between the Nd-loading concentration and scintillator light output will be performed. Studies have shown that by increasing the Nd-loading concentration to 0.3% the light level drops by about a factor of two but the half-life sensitivity increases by 70%.

SNO+ will demonstrate the effectiveness of its technique with natural Nd. However, the possibility of Nd isotopically enriched in ^{150}Nd is enticing and there are a few potential

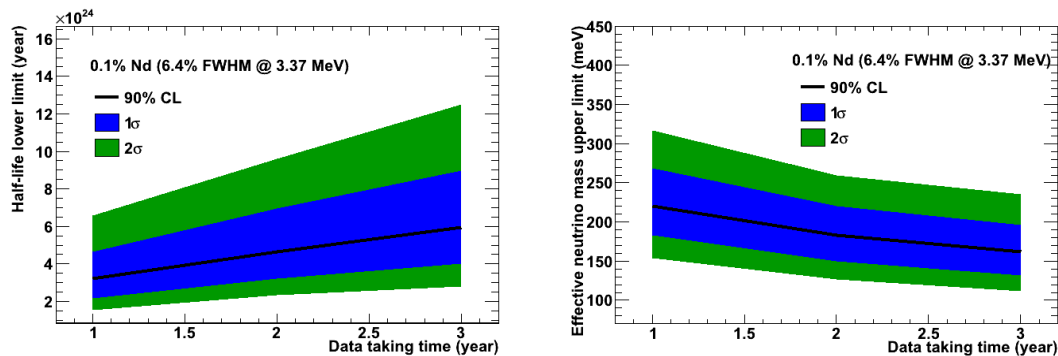


Figure 2. (Left) The evolution of the 90% C.L. $0\nu\beta\beta$ half-life sensitivity over a 3 year run with 0.1% loading of Nd. (Right) The same calculation but showing the 90% C.L. effective neutrino mass sensitivity.

approaches including Atomic Vapour Laser Isotope Separation (AVLIS) and high-temperature centrifuge. Nd enriched to 80% ^{150}Nd would increase the potential number of signal events by a factor of 16. As a simple example, if the experiment were to run 16 times longer then a factor of 2 increase in mass sensitivity would be expected. However, with enriched Nd, backgrounds from ^8B solar neutrinos and also potentially ^{208}Tl would stay constant indicating that more than a factor of 2 increase in mass sensitivity could be possible. With an eye to the future, a particular advantage of scintillator detectors like SNO+ is that a variety of isotopes can be used, providing several different potential opportunities.

5. Schedule

Data taking with the AV filled with light water will commence in 2012 and construction of the scintillator process systems will proceed in parallel. In 2013 the scintillator that has passed through the purification systems will gradually displace the water over a period of a few months and scintillator-filled data taking will commence.

6. Conclusion

SNO+ is an ultra low background liquid scintillator detector located at SNOLAB, Canada. The central acrylic vessel is surrounded by 7400 tonnes of water shielding and the scintillator also self-shields. The scintillator will be purified initially by distillation and additional in-situ purification techniques will be used as necessary. By loading the 780 tonnes of LAB scintillator with O(tonne) of Nd, an experiment to search for neutrinoless double beta decay can be performed down to an effective neutrino mass of 100-200 meV at 90% C.L. with a 3 year run. SNO+ is fully funded and will take water-fill data in 2012 with scintillator data following in 2013.

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